Pore Size Distribution and Hydraulic Conductivity Affected by Tillage in Northwestern Canada

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ABSTRACT

Tillage management can affect crop growth, in part by altering the pore structure and hydraulic properties of soil. We hypothesized that water retention, pore size distribution, and unsaturated hydraulic conductivity (k) differed under conventional tillage (CT) and no tillage (NT). We evaluated this hypothesis on a Donnelly silt loam (fine-loamy, mixed, frigid Typic Cryoboralf) and a Donnelly sandy loam (coarse-loamy, mixed, frigid Typic Cryoboralf) in northwestern Canada. Soil cores were collected from the 0- to 300-mm depth in 75-mm increments. Water retention was measured at 10 pressure levels from -2 to -400 kPa to calculate pore size distribution and k. Both soils retained 0.04 to 0.09 $m^3 m^{-3}$ more water under NT than under CT. The volume fraction of total porosity with pores <7.5 μm in diameter (effective pores for retaining plant-available water) in the silt loam averaged 0.49 and 0.58 $m^3 m^{-3}$ under CT and NT, respectively, and in the sandy loam averaged 0.39 and 0.51 $m^3 m^{-3}$ under CT and NT, respectively. In contrast, the volume fraction of total porosity with pores >150 μm in diameter (pores draining freely with gravity) in the silt loam averaged 0.29 and 0.23 $m^3 m^{-3}$ under CT and NT, respectively, and in the sandy loam averaged 0.35 and 0.24 $m^3 m^{-3}$ under CT and NT, respectively. Conventional tillage appeared more likely to interrupt capillaries than NT, since large differences in k between tillage regimes were observed below a depth of 75 mm with increasing moisture deficit. Continuous NT management increased water storage of both silt loam and sandy loam soils in this cold, semiarid region.

Soil MOISTURE CONSERVATION is a critical issue in dryland, semiarid grain production systems of the Canadian Prairies (Larney et al., 1994). Reduced tillage management systems, including NT, can be effective in reducing water loss from the soil by leaving a protective layer of crop residues on the soil surface to reduce evaporation (Hatfield and Stewart, 1994). Further, soil pore size distribution and structure can be affected by tillage management to influence water storage and transmission. No-tillage management can enhance the surface soil environment for greater faunal and microbial activity (Doran, 1980; House et al., 1984), which rearrange and biochemically alter the soil fabric to achieve improved soil structure (Lal et al., 1980).

Drainage following rainfall occurs primarily within large pores, which are only able to maintain low matric pressure. Conversely, under dry soil conditions, transmission of water across a matric gradient occurs more rapidly through small pores than large pores. Soil water storage and transmission can, therefore, be manipulated with alteration of pore size distribution. Pores >15 μm in diameter occupied more volume under moldboard plowing than under NT in two of three silt loams in Maryland (Hill, 1990). Lack of difference in pore size distribution between tillage regimes on one of the soils was attributed to higher clay content. However, a clay loam under moldboard plowing had a greater volume of pores with diameters >15 μm than under NT, but not in a second clay loam in Iowa (Hill et al., 1985). The volume fraction of pores >150 μm in diameter was greater under chisel and moldboard plowing than under NT in two silt loams, but not different in a silty clay loam, silt loam, and loam from Iowa and Ohio (Benjamin, 1993). The effect of soil texture controlling the potential change in pore size distribution due to tillage does not appear to be clearly defined.

Information on potential changes in soil water storage and transmission properties due to tillage management in the semiarid Canadian Prairies is lacking. Knowledge of these potential changes in soil physical properties is of special interest because of the inherently high organic matter content and structural stability of soils in the frigid region of North America compared with the mesic region (Kemper and Koch, 1966), where most previous studies of tillage effects on pore size distribution and k have been conducted.

We determined water retention, pore size distribution, and k on a silt loam and a sandy loam that were subjected to continuous CT and NT.

MATERIALS AND METHODS

Field experiments were initiated in 1979 on a Donnelly silt loam near Dawson Creek, BC (55°46' N, 120°21' W) and in 1988 on a Donnelly sandy loam near Rolla, BC (55°42' N, 120°10' W). The silt loam contained an average of 260 g clay and 25 g organic C kg^{-1} soil in the 0- to 225-mm depth and 560 g clay and 10 g organic C kg^{-1} soil in the 225- to 300-mm depth. The sandy loam contained an average of 180 g clay and 20 g organic C kg^{-1} soil in the 0- to 225-mm depth and 305 g clay and 10 g organic C kg^{-1} soil in the 225- to 300-mm depth. Annual temperature averages 0.9°C and precipitation averages 504 mm, with 289 mm occurring from May through

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Abbreviations: CT, conventional tillage; k, unsaturated hydraulic conductivity; LSD, least significant difference; NT, no tillage, LSD, least significant difference.

September. Barley (*Hordeum vulgare* L.) was grown continuously on the silt loam and barley and canola (*Brassica campestris* L.) were rotated on the sandy loam. Both soils were managed with CT and NT. Conventional tillage consisted of chiseling to a depth of 120 to 150 mm after harvest and disking twice to a depth of 80 to 100 mm in the spring. No soil disturbance occurred with NT except for planting. Both crops were seeded with a double-disk press drill in 170-mm-wide rows. Plots (5 by 30 m) were four side-by-side locations within adjacent CT and NT fields on both soils.

Triplicate, undisturbed soil cores were collected to a depth of 300 mm in 75-mm depth increments midway between crop rows (avoiding recently trafficked areas) on 25 June 1992 and 1993 (41 and 25 d after planting in the silt loam and 29 and 39 d after planting in the sandy loam, respectively) with a Uhland sampler (75-mm diam.).

Cores were saturated in a shallow water bath for at least 4 d. Water retention was determined successively at -2, -5, -10, -20, -30, and -40 kPa using a volumetric pressure-plate extractor (Model 1250, Soil Moisture Equipment, Santa Barbara, CA) and at 60, 120, 220, and 400 kPa using a pressure-plate apparatus for each replication of each treatment. Water retention data were fitted to the equation:

$$\psi = \psi_e \, (\theta/\theta_{sat})^{-b}$$

where ψ is the matric pressure, ψ_e is the intercept (also termed the air-entry point), θ is volumetric water content at a given matric pressure, θ_{sat} is volumetric water content at saturation, and b is an empirically derived constant describing the slope of the relationship between matric pressure and relative saturation. Total porosity was determined from the equation:

$$\text{total porosity} = 1 - \rho_b/\rho_p$$

where ρ_b is bulk density (Mg m^{-3}) and ρ_p is particle density (assumed 2.65 Mg m^{-3}). Bulk density was determined from oven-dried cores (105°C, 24 h) following water retention determinations.

Mean pore diameter at a given matric pressure was estimated from water retention using the following equation (Danielson and Sutherland, 1986):

$$d_p = 4 \, \sigma \, 10^5 \, / \, (\rho_w \, g \, h)$$

where σ is surface tension of water (0.0735 J m^{-2} at 22°C), ρ_w is density of water, g is gravitational acceleration, and h is the matric pressure (kPa).

Saturated hydraulic conductivity to a depth of 300 mm in 75-mm depth increments was determined in the field using a Guelph permeameter (Reynolds, 1993). Unsaturated hydraulic conductivity was calculated from water retention and saturated hydraulic conductivity using the equation (Campbell, 1974):

$$k = k_{sat} \, (\theta/\theta_{sat})^{2b+3}$$

where k_{sat} is saturated hydraulic conductivity.

Analysis of variance was used to determine tillage effects on bulk density, b, volume fraction of pores, and k at each matric pressure for each depth of each soil (SAS Institute, 1990). Tillage means were separated with a LSD at $P \le 0.05$.

RESULTS AND DISCUSSION

Soil bulk density was greater in the sandy loam than in the silt loam, resulting in less total pore space in the sandy loam, but equal pore space between tillage regimes within a depth for each soil (Table 1). Several studies have reported higher bulk density under NT at the soil surface compared with tilled soil (Hill, 1990; Wu et al.,

Table 1. Soil bulk density, water retention constant (b) from the equation, $\psi = \psi_e \, (\theta/\theta_{sat})^{-b}$ and saturated hydraulic conductivity in a Donnelly silt loam and a Donnelly sandy loam as affected by conventional tillage (CT) and no tillage (NT) to a depth of 300 mm.

	Silt loam		Sandy loam	
Soil depth	CT	NT	CT	NT
mm				
Soil bulk density (Mg m^{-3})				
0–75	1.23	1.25	1.36	1.37
75–150	1.26	1.26	1.37	1.36
150–225	1.33	1.33	1.41	1.41
225–300	1.34	1.35	1.42	1.40
Water retention constant (b)				
0–75	7.6 *	7.9	3.5 *	3.9
75–150	7.7 *	11.0	3.2	3.8
150–225	10.7	13.9	2.8 *	3.9
225–300	7.7 *	11.6	3.4 *	3.5
Saturated hydraulic conductivity (mm d^{-1})				
0–75	13.1 *	18.5	190.2 *	267.9
75–150	14.9 *	31.8	196.9 *	232.4
150–225	5.6	7.9	161.3	158.3
225–300	12.2	13.1	182.7 *	392.8

* Significant difference between tillage means at $P \le 0.05$.

1992; Gregorich et al., 1993). Benjamin (1993) reported increased bulk density with NT compared with chisel plowing in three of six soils in Iowa and Ohio, no difference between tillage in two soils, and lower bulk density with NT in one soil. The time of sampling after tillage and preceding rainfall is an important factor controlling differences in bulk density between tillage regimes (Franzluebbers et al., 1995). We collected soil samples from 25 to 41 d after planting so that any disturbance in bulk density at planting would have subsided. This sampling period was also early enough in the growing season to reflect soil conditions during active crop root growth.

At a given matric pressure, soil under NT retained more water than soil under CT in both soils (Fig. 1). The b value derived from the relationship between matric pressure and relative saturation was greater in the silt loam than the sandy loam at all depths (Table 1). The greater the b value, the greater the water retention across a range of matric pressures. Soil under NT retained more water than under CT in the 0- to 75-mm depth of both soils, suggesting significant rearrangement of pores near the soil surface. However, greater difference in water retention between tillage regimes of both soils occurred at lower depths. Greater water retention in the Ap horizon under NT than under moldboard plowing was also observed in a silt loam, but not in a clay loam (Wu et al., 1992). In a field determination, more water was retained in a silt loam under NT than under moldboard plowing (Datiri and Lowery, 1991).

The majority of pores within each soil and tillage regime was <50 µm in diameter (Table 2). The volume fraction of total porosity with pores <7.5 µm in diameter was 0.06 to 0.12 m^3 m^{-3} greater under NT than under CT in the silt loam and 0.07 to 0.27 m^3 m^{-3} greater in the sandy loam within different depths. Volume fraction of total porosity with pore diameters from 7.5 to 50 µm occupied from 0.03 to 0.04 m^3 m^{-3} less under NT than
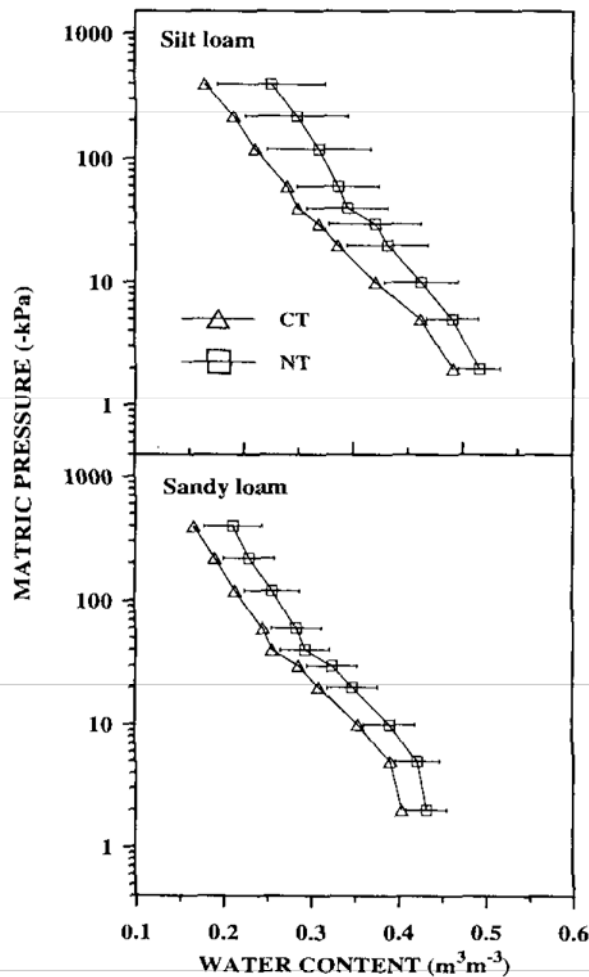
Fig. 1. Matric pressure as a function of soil water content averaged across depths for a Donnelly silt loam and a Donnelly sandy loam as affected by tillage. (CT is conventional tillage and NT is no tillage. Error bar is least significant difference at $P \leq 0.05$).

depth (Table 2). Few differences in the volume fraction of total porosity with mean pore diameters from 50 to 150 μm occurred between tillage regimes in both soils. Approximately half of the difference in volume between tillage regimes for pores with diameters <7.5 μm was reallocated to pores with diameters from 150 to 1500 μm for both soils. No differences in the volume fraction of total porosity with pores >1500 μm in diameter between tillage regimes occurred in the silt loam. However, in the sandy loam, the volume fraction of pores >1500 μm in diameter was 0.05 to 0.07 m^3 m^{-3} less under NT than under CT.

The effect of NT management in both the silt loam and the sandy loam was to reduce the volume fraction of large pores and increase the volume fraction of small pores relative to CT management. This result is not consistently supported in other studies. Greater volume fraction of total porosity with pores >150 μm in diameter in tilled systems compared with NT occurred in three of eight sites (Hill et al., 1985; Benjamin, 1993). The effect of tillage management on the volume of large pores appears to be soil and cropping system specific, and therefore needs to be determined further under different environmental conditions.

Pores with diameters between 0.1 and 15 μm are assumed to retain more plant-available water than larger pores (Hill et al., 1985). Presence of an average of 0.09 m^3 m^{-3} greater volume fraction of total porosity with pores <7.5 μm under NT than under CT in the silt loam and 0.12 m^3 m^{-3} greater in the sandy loam suggests that more water can be stored for potential plant uptake with NT management in this cold, semiarid climate. In the temperate, subhumid climates of Iowa and Ohio, the volume fraction of total porosity with pores <15 μm in diameter increased to a similar magnitude as in our study with NT compared with tilled systems at two sites, but was not different or was less at four sites (Benjamin, 1993). Further research is needed to explain why pore size distribution is affected by tillage in some soils and not in others.

Greater k was calculated for both soils under NT than under CT with increasing moisture deficit below 75-mm

under CT in the silt loam at two soil depths, but did not differ between tillage regimes in the sandy loam when averaged to the 0.3-m depth, despite a significantly greater volume fraction under CT at the 150- to 225-mm

Table 2. Volume fraction of total porosity with pore diameters within selected size classes and total porosity in a Donnelly silt loam and a Donnelly sandy loam as affected by conventional tillage (CT) and no tillage (NT) to a depth of 300 mm.

	Pore volume/total porosity													
	<7.5 μm			7.5–50 μm			50–150 μm			150–1500 μm			>1500 μm		Total porosity
Soil depth	CT		NT	CT		NT	CT		NT	CT		NT	CT	NT	CT	NT
mm											m^3 m^{-3}					
							Silt loam									
0–75	0.45	*	0.51	0.15		0.15	0.10		0.11	0.20	*	0.16	0.10	0.08	0.54	0.53
75–150	0.47	*	0.59	0.21	*	0.17	0.05		0.05	0.18	*	0.12	0.09	0.08	0.52	0.52
150–225	0.55	*	0.62	0.10		0.08	0.07		0.06	0.19	*	0.15	0.10	0.09	0.50	0.50
225–300	0.48	*	0.60	0.12	*	0.09	0.10	*	0.06	0.22	*	0.17	0.09	0.09	0.49	0.49
0–300	0.49	*	0.58	0.14	*	0.12	0.08		0.07	0.20	*	0.15	0.09	0.08	0.51	0.51
							Sandy loam									
0–75	0.42	*	0.49	0.05		0.06	0.14		0.15	0.23		0.19	0.17	*	0.11	0.49	0.48
75–150	0.44	*	0.53	0.16		0.18	0.09		0.06	0.17		0.14	0.15		0.10	0.48	0.49
150–225	0.30	*	0.57	0.21	*	0.12	0.17		0.16	0.18	*	0.09	0.14	*	0.07	0.47	0.47
225–300	0.40	*	0.47	0.11		0.12	0.14		0.18	0.23	*	0.17	0.13	*	0.07	0.46	0.47
0–300	0.39	*	0.51	0.13		0.12	0.13		0.14	0.20	*	0.15	0.15	*	0.09	0.48	0.48

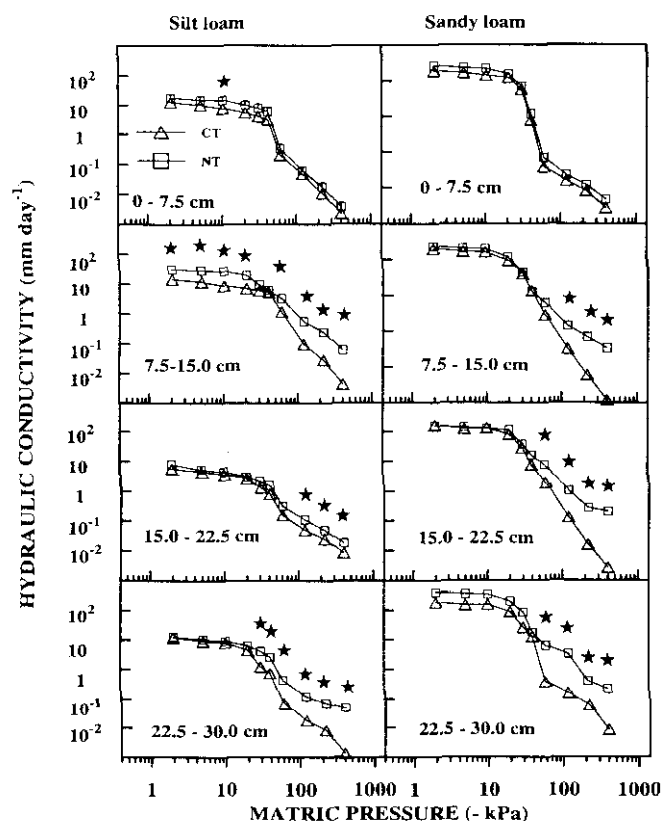* Significant difference between tillage means at $P \leq 0.05$.

Fig. 2. Calculated unsaturated hydraulic conductivity as a function of matric pressure for a Donnelly silt loam and a Donnelly sandy loam as affected by depth and tillage using the equation, $k = k_{sat} (\theta/\theta_{sat})^{2b+3}$. (CT is conventional tillage and NT is no tillage. *Significant difference between tillage regimes at $P \leq 0.05$).

soil depth (Fig. 2). Greater k with NT than with CT is probably a result of the greater volume fraction of pores <7.5 μm in diameter, which transmit water faster across a matric pressure gradient than do larger pores. The large difference in k also suggests that the pores under NT may be more continuous than under CT, resulting in greater water movement with NT. Tillage can disrupt pore continuity, especially within the tilled zone and between the tilled and untilled zone (Kay, 1990). Pore continuity was observed at a depth of 350 mm at all four sites in Minnesota and Wisconsin with NT, but only at one site with moldboard plowing (Logsdon et al., 1990). Pore continuity was greater after only 2 yr of NT at a depth of 80 to 240 mm than with moldboard plowing in a fine sandy loam in Prince Edward Island (Carter, 1992). In the same study, NT had less pore continuity than with shallow tillage at 0- to 80-mm depth, similar continuity at 80- to 160-mm depth, and greater continuity at 160- to 240-mm depth.

Our calculated results of greater k under NT than under CT at matric pressures less than -40 kPa and at depths <75 mm in both soils have rarely been found previously. Greater k under NT than CT was observed only at matric pressures below -200 kPa for a loess soil in Germany, with lower k under NT than under CT at matric pressures approaching saturation (Frede et al., 1994), suggesting that the native soil structure prior to imposition of tillage management or some other environ-

mental factor may be of importance in regulating near-saturated flow with contrasting tillage regimes.

Few differences in k were observed between tillage regimes at matric pressures greater than -60 kPa (Fig. 2). This observation was a result of more large pores, but lower saturated hydraulic conductivity (Table 1) and lower b value with CT than NT. These opposing effects on k suggest that water transmission through small pores, which may also be better connected under NT, contribute a great deal to water transmission under both near-saturated and dry conditions in both the silt loam and sandy loam. Greater k with NT than with moldboard plowing in the Ap horizon of a clay loam from Minnesota was found at -10 kPa, but not at -30 kPa (Wu et al., 1992). No difference in k between tillage regimes at either -10 or -30 kPa was found in a silt loam from Wisconsin (Wu et al., 1992). No differences in k between NT and either chisel or moldboard plowing were observed at matric pressures of -4 to -42 kPa in a silt loam from Wisconsin (Datiri and Lowery, 1991).

CONCLUSIONS

In the cold, semiarid climate of the Canadian Prairies, a silt loam and a sandy loam could be effectively managed with continuous NT to increase water storage by $\approx 7\%$ at -30 kPa and $\approx 9\%$ at -400 kPa and increase potential water transmission severalfold at matric pressures ≤ -120 kPa. Crops managed with NT in this area would appear to be better suited to tolerate water-limiting situations than crops managed with CT, due to rearrangement of pore size classes for more effective water storage within fine pores.

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ERRATUM

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On p. 1198, left-hand column, in equation 3, the unit of *h* (matric pressure) is in cm and not in kPa. As a result of this error the values of the pore size diameter in table 2 and elsewhere in this paper are off by an order of magnitude. For example, the pore size diameter should be <0.75, 0.75-5, 5-15, 15-150 and >150μm in stead of <7.5, 7.5-50, 50-150, 150-1500 and >1500μm in the header of table 2.